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RF CONTROL SYSTEM FOR A ROCKET-BORNE ACCELERATOR*

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Abstract

The Beam Experiments Aboard Rockets (BEAR) accelerator experiment imposes several nonstandard requirements on the rf control system. The experiment is entirely hands-off and must operate under local computer control. The rf control system must be extremely reliable, which implies excellence in design and fabrication as well as redundancy whenever possible. This paper describes the design of the frequency-source, frequency-control, and amplitude-control systems for the BEAR experiment.

Introduction

The Beam Experiments Aboard Rockets (BEAR) program is a suborbital rocket flight to demonstrate the autonomous operation of an accelerator and to observe the beam propagation. The "one-shot" nature of the experiment places added emphasis on the system reliability. If a redundant part does fail, the failure must be transparent and not cause the failure of any other part of the operating system. Shock, vibration, and large temperature excursions have been considered in component selection. The circuit boards and enclosures have been carefully designed to be sturdy and as lightweight as possible. Finally, the entire rf system must be electrically efficient to conserve battery power.

System Description

The pertinent specifications for the rf system are shown in Table I. The average beam current during the macropulse will be 26 mA with an output energy of 1 MeV. A block diagram of the rf system is shown in Fig. 1. The Defense and Electronic Systems Center of the Westinghouse Electric Corporation designed and built the high-power amplifiers. The minimum specified power capability for each amplifier is 60 kW. Two amplifiers are required to provide the nominal 100 kW for the BEAR experiment. The additional power capability of 20 kW is required for reliability and to provide for a sufficient amplitude-control margin. Each amplifier has its own internal phase and amplitude control loops. The primary purpose of the internal control loops is to provide amplitude and phase control of amplifiers over the required operating range. These internal control loops must respond to command variations of 1 dB in amplitude and 30° in phase with a settling time of less than 1 μs.

In addition to these internal control loops in the high-power amplifiers, there is an external rf control system to maintain the proper field levels in the radio-frequency quadrupole (RFQ), to control the frequency of the source oscillator, and to interface with the on-board controller and telemetry system. The external rf control system consists of a dual amplitude-control circuit, a dual frequency-source/frequency-control system, a dual power regulator, and the signal interface to the on-board controller and telemetry system.

The RFQ is the only cavity involved in the BEAR experiment, and the input to the RFQ is a dc beam (over the width of the rf macropulse). The two amplifiers are, therefore, the only items that must maintain a constant relative phase.

In addition, as mentioned above, the high-power amplifiers have internal phase-control loops to ensure that the phase shift through the amplifiers is constant. For

TABLE I

BEAR RF SYSTEM SPECIFICATIONS

RF Specifications:	
Frequency	425 MHz
Pulse length	60 μs
Repetition rate	5 Hz
Total mission time	400 s
Power required by RFQ	100 kW
Power capability	120 kW (minimum)
Output beam energy	1 MeV
Control Specifications:	
Amplitude control	Preset ± 1%
Frequency range	425 ± 0.5 MHz
Frequency control	$F_{resonance}$ ± 20 kHz
Environmental Specifications:	
Shock	50 G
Vibration	0.025 g^2/Hz
Temperature	-65°F to 130°F
Ambient Pressure	1 atm, nitrogen

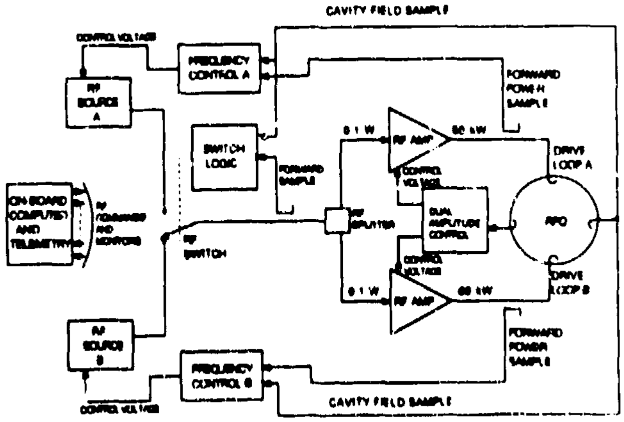

Fig. 1. Block diagram of BEAR rf system. The rf control system features a dual redundant source/frequency controller and a dual redundant amplitude controller.

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these reasons, a phase-control loop around the cavity is unnecessary.

Conservation of electrical power is mandatory in many areas. For example, the relay used to switch between rf sources is a latching, coaxial relay that requires power only when switching. Power conserving CMOS and LS-TTL circuits are used wherever possible. A minimal number of operational amplifiers are used in the control circuits. The Westinghouse amplifiers are deenergized between macropulses except for a minimal number of housekeeping circuits. Because of this deenergization, these amplifiers require an rf "prefire" pulse approximately 0.5 ms before each macropulse to return the circuits to an operational mode before the rf gating pulse is received.

Amplitude Control

The external amplitude-control loop is a dual, redundant controller. A block diagram of the amplitude controller is shown in Fig. 2. Each branch of the controller

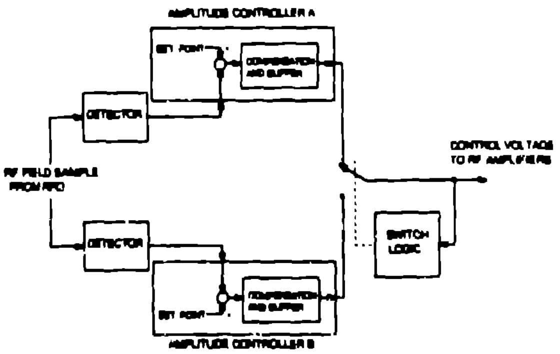

Fig. 2. Block diagram of BEAR dual, redundant rf amplitude controller. The output-control voltage is monitored by the switch logic. If the output-control voltage is not within the correct range, the unused amplitude controller is selected.

has its own diode detector and set-point voltage. The value for the set point will be determined during ground testing and will be fixed for the actual flight. To keep the system as simple as possible for the flight, the set point is not under computer control. Each amplitude controller uses integral/proportional (IP) compensation (Fig. 3). This compensation achieves small error (because of integral control) and reasonable bandwidth (because of proportional control) in a simple circuit. The integrator capacitor has a bleed resistor across it to reset the voltage to zero between macropulses. This avoids the use of reset switches and the associated monitoring and control circuits.

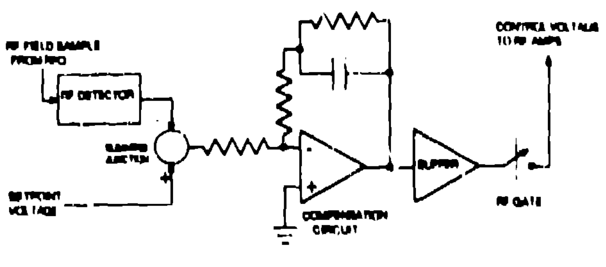

Fig. 3. Block diagram of amplitude-controller circuit. The compensation circuit employs integral and proportional control.

A particular amplitude controller is selected by connecting the output voltage of the circuit to the input of the Westinghouse amplifiers. The unused controller is still operating but is not connected in the loop. The amplitude-control switching logic monitors the control voltage from the amplitude controller in a dual-ended comparator. A switch request is generated if the output voltage is outside the limits of the comparator circuit. The comparator must be dual-ended to detect failures that drive the output full on (such as a loss of the detected feedback signal) as well as failures that can turn the output voltage off (such as a loss of the set-point voltage). Switching between the two amplitude controllers is done only during the interval between rf macropulses.

Frequency Source and Control

Many ground-based linear accelerators control the resonant frequency by controlling the temperature of the accelerator cavities. This technique allows the use of a fixed-frequency oscillator as the master oscillator. However, temperature-control loops are relatively slow and require a water system to control the accelerator temperature. The mission time for BEAR is short (~400 s), and weight is one of the primary concerns in the project. In addition, the duty cycle for BEAR is small (3×10^{-4}), so the expected change in resonant frequency of the RFQ caused by thermal effects is small. As a result, we will not control the temperature of the RFQ. Instead, a Voltage-Controlled Oscillator (VCO) and a Phase-Locked Loop (PLL) will be used to find and track the resonant frequency of the RFQ during the mission. Bench tests have shown that the frequency-control system can find and lock onto the resonant frequency of a cavity with features similar to the BEAR RFQ in 3- to 5-rf macropulses of 60 μs. This locking can occur over a range of ±0.5 MHz (the range of the VCO).

A block diagram of the frequency source and control system is shown in Fig. 4. To minimize the number of switches in the system, a frequency controller is connected to each VCO. A switch request to change to the other system is generated if either the frequency controller or the VCO fails.

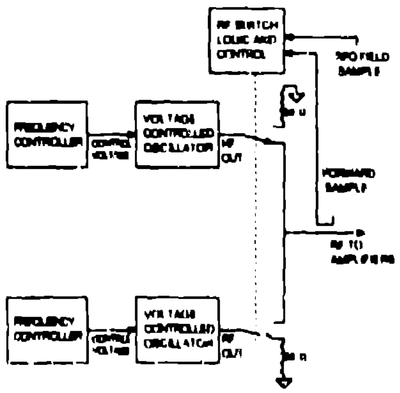

Fig. 4. Block diagram of dual, redundant frequency controller/rf source. The switch logic switches to the unused circuit if the output of the VCO is too low or if the RFQ field sample does not reach the appropriate level within a predetermined number of rf pulses.

Frequency Source

The VCO is a commercial product that was purchased with environmental specifications consistent with the

BEAR experiment. The VCO works over a range of 425 ± 0.5 MHz with a ±5-V control-voltage input giving a constant of 0.1 MHz/V. Both oscillators will be operating throughout the mission, but only one will be driving the high-power amplifiers. The latching relay that selects which system is being used provides a matched load for the unused oscillator so that its power will be properly dissipated under all operational circumstances.

Frequency Controller

The frequency controller consists of three parts: (1) the PLL that locks onto and tracks the resonant frequency of the RFQ, (2) the frequency-ramping circuit that ramps the VCO to quickly find the approximate resonant frequency of the RFQ, and (3) the switch-selection logic that determines whether or not the frequency controller is functioning properly and generates a switch request if the controller is malfunctioning. Without the frequency-ramping circuit, it could take several minutes for the PLL to find the resonant frequency. Because the mission is only a few minutes long, we could not afford a long lock-up interval. The design thus requires a fast lock-up mechanism.

A block diagram of the frequency-control circuit is shown in Fig. 5. The components that make up the PLL

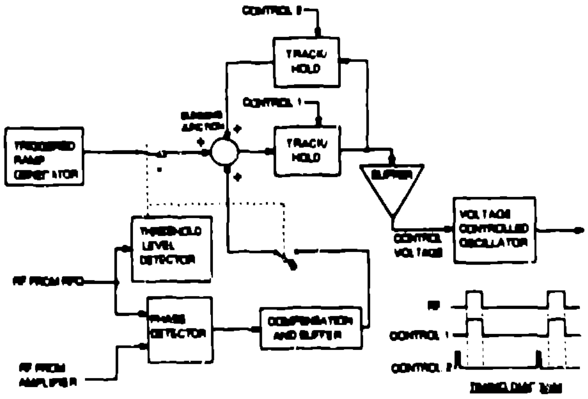

Fig. 5. Block diagram of frequency-controller circuit. The ramp generator quickly brings the VCO very close to the correct frequency. The threshold detector then disconnects the ramp generator and connects the PLL to fine tune the VCO frequency. The PLL consists of the phase detecor, the compensation and buffer circuit, the VCO, and the power amplifier and RFQ (not shown).

are the phase detector, the compensation and buffer, the VCO, the high-power amplifier (not shown), and the RFQ (not shown). Whenever the circuit detects that it is not on the resonant frequency, such as during the initial startup, the triggered-ramp generator is enabled and the PLL is disabled. This quickly ramps the VCO during each macropulse while the logic circuitry samples the cavity field level. It takes approximately five 60-μs rf pulses for the ramp to swing the VCO over its entire range. After covering the entire range of the VCO, the circuit resets and begins the ramping all over again until it finds the resonant frequency. The detected field level in the RFQ is compared to a preset level in a single-ended comparator. The resonant frequency is detected when the field level exceeds the preset level.

After the ramp finds the approximate resonant frequency, the ramp is disabled and the PLL is enabled in order to "fine tune" the VCO frequency and to track any changes in the RFQ frequency. Between rf macropulses, the VCO control voltage is stored in a sample-and-hold circuit. As a result, the VCO starts each macropulse at the same frequency as the previous pulse. This allows the integrator in the PLL to work over its maximum dynamic range. The integrator only has to follow the small changes in frequency that will occur during the macropulse because of temperature fluctuations and/or beam loading. The frequency controller must find the resonant frequency to within ±20 kHz to guarantee both sufficient gain margin for the amplitude controller and drive capability by the high-power amplifiers. The operation of the frequency controller in a breadboard configuration is shown in Fig. 6. The operation of the ramp generator and the takeover by the PLL can be clearly seen.

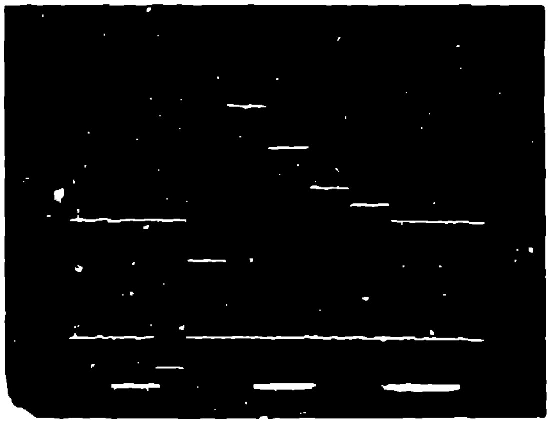

Fig. 6. Oscilloscope photograph showing the action of the frequency controller. Vertical scale is 2V/division. Horizontal scale is 200 ms/division.

Bottom Trace: Manual switching of the rf to induce searching by the frequency controller. Up is rf on, and down is rf off.

Upper Trace: Control voltage from the frequency controller. The ramp and hold action appears as the staircase. After the rf is turned back on, it takes approximately five steps to find the resonant frequency.

Switching Logic

The switch-control logic pulses a latching coaxial relay to select which VCO/frequency controller is being used (see Fig. 4). The switch request is generated only during the interval between rf macropulses. The control logic generates a switch request if it detects a failure in either the VCO or the frequency controller. A failure in the VCO will manifest itself by a loss of output signal. This is detected by sampling the signal level coming out of the VCO and comparing it with a preset level in a comparator. A failure of the frequency controller is detected by counting the number of rf macropulses required to find resonance. If the number of pulses exceeds a preset number (say 10), the logic circuit will generate a switch request to change to the unused frequency controller.

Conclusions

The BEAR rf control system has presented a set of unique requirements. The requirements have been met by simplifying the circuits as much as possible and by using redundancy in several critical areas (that is, wherever the circuit overhead is small enough that it does not have a major impact on space, weight, or power consumption). The circuits have been breadboarded, and the test results meet the system requirements.